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# Electrical current influence on resistance and localization length of a Co–$Al_2O_3$ granular thin film

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ABSTRACT

Electrical, magnetic and magnetotransport properties were measured in a Co–$Al_2O_3$ granular film. Electrical resistance was obtained in the low-field regime ($e\ \Delta V \ll k_BT$) under variation of injected current and bias and as a function of temperature and bias. Electrical properties were best described with the model of variable range hopping, where the electrical resistance decreases and the electronic localization length increases with increase of the applied bias and/or current. We associate this behavior to the activation of new electronic paths between more distant grains, reducing the total resistance whilst additional parallel paths are formed. This behavior is similar to results obtained with Fe–$Al_2O_3$ granular thin films, which however have a higher range of resistance variation.



## 1. Introduction

The electrical and magnetotransport properties of metal/insulator granular systems have been extensively studied by many research groups [1]. In these systems the electrical current is due to electrons tunneling between grains. Many magnetotransport effects have been verified in these systems, such as tunnel magnetoresistance [2] and giant Hall effect [3], which make metal/insulator granular thin films good candidates for the development of technological applications. The granular Co–$Al_2O_3$ is one of the most studied metal/insulator systems [3,4], and its films present tunnel magnetoresistance and high order tunneling at low temperatures [4]. Recently, we have reported on the modification of electrical properties of metal/insulator granules when the electrical current and/or bias potential was increased in the low-field regime [5]. In the present study we investigate the influence of electrical current on the electrical properties in a Co–$Al_2O_3$ sample, establishing a similar dependence of resistance and localization length on current as observed in Fe–$Al_2O_3$ [5] granular films. We present a model that explains the observed electrical properties when the applied current is increased.

## 2. Experiment

Different from many former granular films, where the insulator was made by reactive sputtering in oxygen atmosphere, this film was co-sputtered at room temperature from Co and $Al_2O_3$ targets onto a glass substrate. The cobalt volume fraction ($x$) obtained with Rutherford backscattering spectrometry (RBS) was close to 0.5. Grazing incidence X-ray diffractometry (GIXRD) showed that the cobalt atoms arranged themselves into grains of closed-packed hexagonal structure with 1.6 nm mean diameter. The film thickness, estimated with X-ray absorption in the Seemann–Bohlin geometry, was around 200 nm.

The distance between grain centers was calculated from the metal volume fraction and Co-grain size and estimated to be around 20 Å. The voltage drop between neighboring grains was estimated to be less than 0.04 mV when 20 V was applied between the electrodes, which is much smaller than $k_BT$ and indicates that in our experiments the low-field regime assumption holds [8].

Magnetization ($M$) was obtained using an alternating gradient field magnetometer at room temperature. Resistance ($R$) measurements as a function of temperature ($T$) were performed using the four-point method. The resistance was obtained in the voltage range of 0 to 14 V. Magnetoresistance ($MR$) was measured parallel and perpendicular to the applied magnetic field ($H$), with maximum $H$ of 4 kOe. Magnetoresistance was defined as $MR=(R(0)-R(H))/R(0)$.

## 3. Results and discussion

In Fig. 1a $M$ vs. $H$ measurements show that the Co-$Al_2O_3$ sample presents superparamagnetic behavior at room temperature. The $R$

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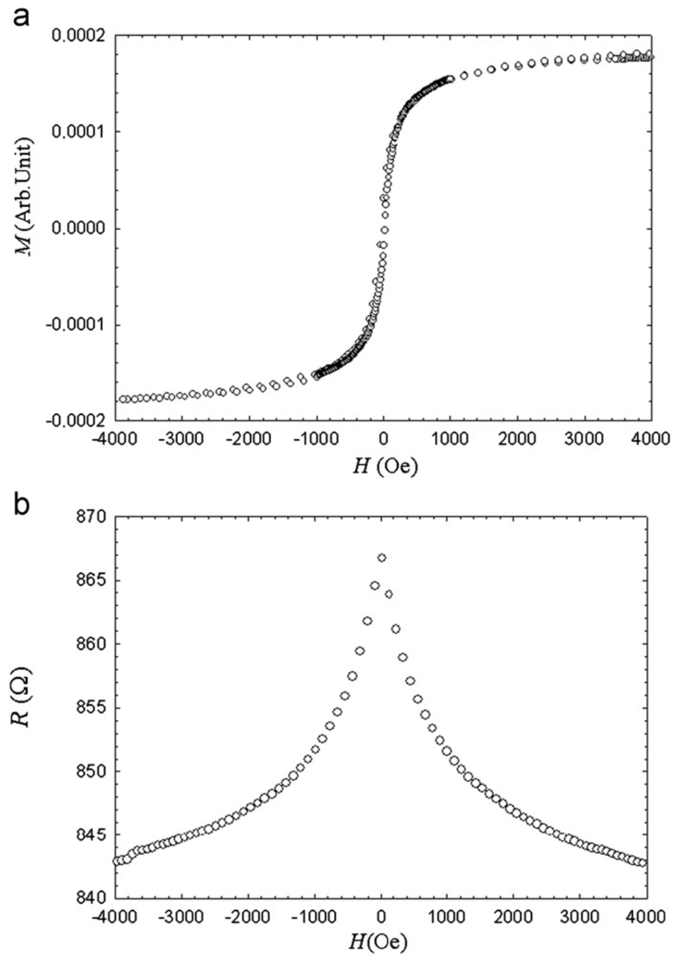


**Fig. 1.** (a) $M$ vs. $H$ and (b) $R$ vs. $H$ measurements performed at room temperature for the Co–$Al_2O_3$ sample.

vs. $H$ curve with electrical current longitudinal to the magnetic field is shown in Fig. 1b. It can be noticed that the electrical resistance decreases when the magnetic moment of the grains is parallel to the magnetic field, characteristic of spin dependent tunneling. The magnetoresistance measurements did not show anisotropy at room temperature and $MR$ was equal to 2.6%.

A smooth decrease of resistance with increasing voltage was observed at 150 K (Fig. 2). Compared to Fe–$Al_2O_3$ granular films [8] this film showed lower resistance variation, no plateau and sudden drop in the $R$ vs. $V$ curve.

The behavior of $R$ as a function of $T$ in granular thin films is described by the following equation [1,2]:

$$R = R_0 \exp(T_0/T)^{\alpha}, \tag{1}$$

where $T_0$ is given by $18.1/(k_B\, g_0\, \xi^3)$, where $g_0$ is the constant Mott density of states and $\xi$ is the localization length. $T_0$ depends on the metal concentration and $\alpha$ can assume values of 1/2 for thermally activated hopping [1] and 1/4 for variable range hopping [6]. Fig. 3a presents the data as a ln $R$ vs. $T^{-1/2}$ plot and a fitting curve using thermally activated hopping, while Fig. 3b presents the data as a ln $R$ vs. $T^{-1/4}$ plot and a fitting curve using variable range hopping. It can be seen that the $T^{-1/4}$ fit adjusts our data much better than the $T^{-1/2}$ fit.

When the electrical current is increased, the resistance shows a slightly modified behavior. Fig. 4 presents the results of ln$R$ vs. $T^{-1/4}$ when the injected current is increased from 0.5 to 10 mA. Even though the linearity of the high current data in the $T^{-1/4}$ plot

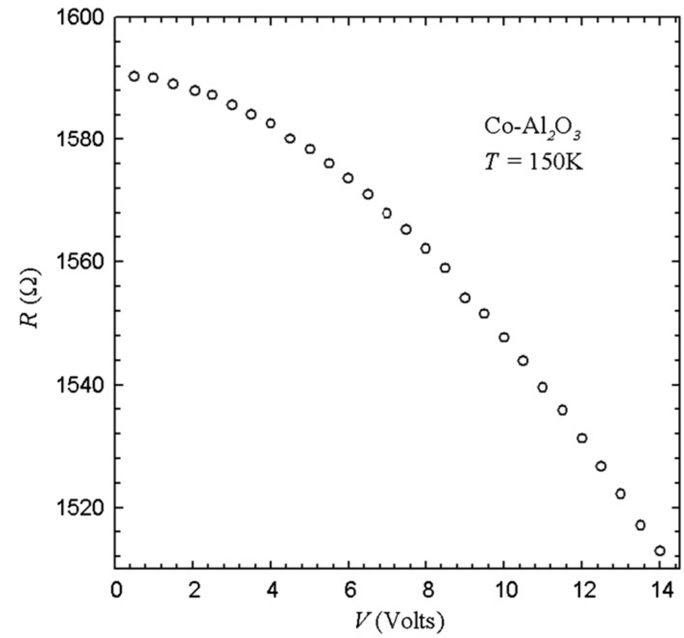


**Fig. 2.** $R$ vs. $V$ measurements for the Co–$Al_2O_3$ sample at $T$=150 K.

is not as good as at low currents, we presumed that the assumption of variable range hopping still holds and that a modification of the localization length occurs when current is increased.

At room temperature, the electrical resistance decreased from 1280 Ω for $I$=0.5 mA to 1247 Ω for $I$=10 mA, while at $T$=43 K, it decreased from 2426 Ω to 1867 Ω in the same current range. The resistance variations due to bias increase were larger at low temperature (559 Ω) than at room temperature (33 Ω), but were smaller than the analogous results obtained in the Fe-$Al_2O_3$ granular film [7,8].

Curve fits using Eq. (1) were performed with data obtained at 100–150 K, and the values of $T_0^{1/4}$, $T_0$ and $R_0$ at different currents are shown in Table 1. Curve fitting procedures performed with data obtained at 40–60 K are shown in Table 2. It was verified that $T_0$ decreased from 305.3 K for currents of 0.5 mA to 41.3 K for 10 mA when the fitting was realized from 100 to 150 K and from 357.3 K for currents of 0.5 mA to 8.1 K for 10 mA when the fitting was realized from 40 to 60 K. This behavior of $T_0$ indicates a larger localization length at higher current and localization length dependence on temperature.

It is possible to interpret the behavior of resistance and localization length with bias increase as an evidence for the activation of new parallel electronic paths between grains. Using the resistance values for $T$=43 K, the calculated resistance of the new parallel path is equal to 8102 Ω, compatible with electrons tunneling between more distant grains. These paths have different hopping distances that increase with the localization length.

## 4. Conclusions

Our results have shown that spin dependent tunneling is present in the Co–$Al_2O_3$ sample, variable range hopping is the best description of electrical properties, $R$ decreases as $V$ or $I$ is increased, $T_0$ depends on temperature and $T_0$ decreases when $I$ increases, implying that the localization length $\xi$ is enlarged. The behavior of $T_0$ is analogous to the one obtained on Fe–$Al_2O_3$ granular films [5,8], but some features of the performance are not

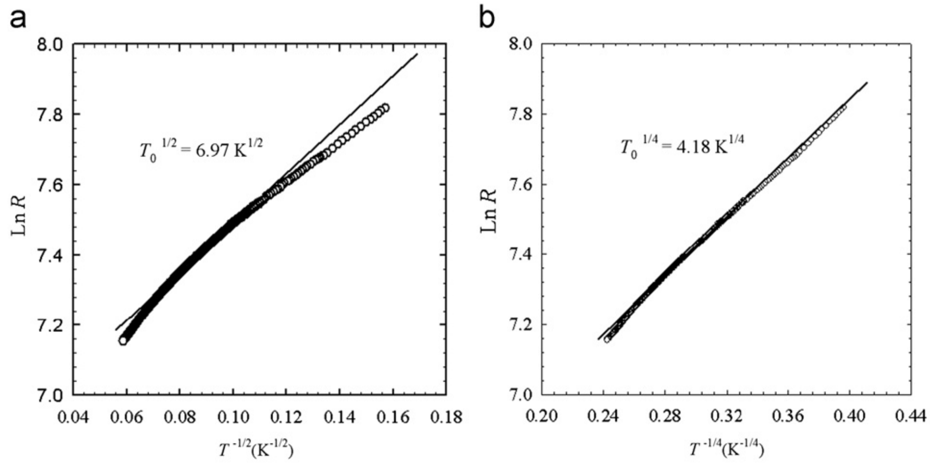


**Fig. 3.** (a) ln$R$ vs. $T^{-1/2}$ plots and (b) ln$R$ vs. $T^{-1/4}$ plots for the Co-$Al_2O_3$ sample. Curve fits using Eq. (1) with $\alpha=1/2$ and with $\alpha=1/4$ are shown.

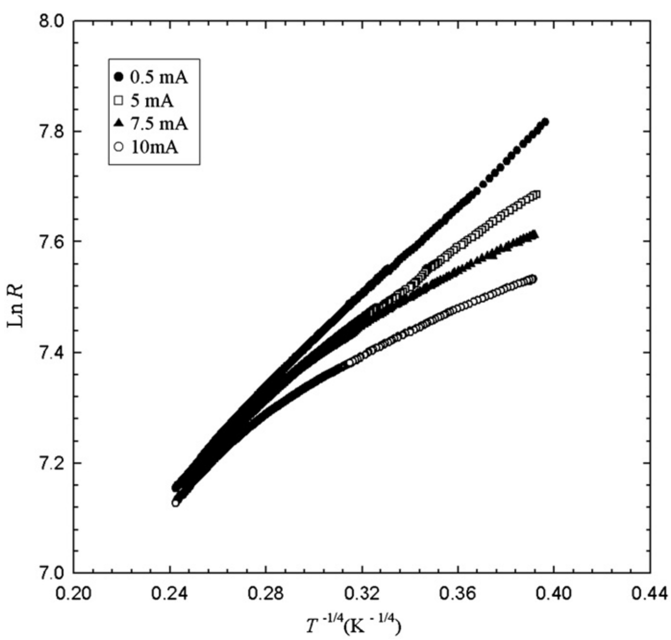


**Fig. 4.** ln $R$ vs. $T^{-1/4}$ for the Co–$Al_2O_3$ sample for injected direct currents $I$ of 0.5 mA, 5 mA, 7.5 mA and 10 mA.

**Table 1**
Values of $T_0^{1/4}$, $T_0$ and $R_0$ obtained for the Co–$Al_2O_3$ sample when fitting the experimental data with Eq. (1) in the temperature range from 100 K to 150 K.

| $I$ (mA) | $T_0^{1/4}$ (K$^{1/4}$) | $T_0$ (K) | $R_0$ (Ω) |
|---|---|---|---|
| 0.5 | 4.18 | 305.3 | 476 |
| 5 | 3.57 | 162.4 | 556 |
| 7.5 | 3.01 | 82.1 | 654 |
| 10 | 2.54 | 41.3 | 720 |

reproduced. This can be due to the change in metal concentration in our Co–$Al_2O_3$ sample when compared to the formerly reported Fe–$Al_2O_3$ films [8].

**Table 2**
Values of $T_0^{1/4}$, $T_0$ and $R_0$ obtained for the Co–$Al_2O_3$ sample when fitting the experimental data with Eq. (1) in the temperature range from 40 K to 60 K.

| $I$ (mA) | $T_0^{1/4}$ (K$^{1/4}$) | $T_0$ (K) | $R_0$ (Ω) |
|---|---|---|---|
| 0.5 | 4.34 | 357.1 | 443 |
| 5 | 2.97 | 78.1 | 679 |
| 7.5 | 1.94 | 14.3 | 990 |
| 10 | 1.68 | 8.1 | 965 |

We interpreted the behavior of resistance and localization length with bias increase as an evidence for the activation of new parallel electronic paths between grains, which accounts for the decrease in total sample resistance.

## References

[1] B. Abeles, Applied Solid State Science: Advances in Materials and Device Research, in: R. Wolfe (Ed.), Academic, New York, 1976, p. 1.
[2] H. Fujimori, S. Mitani, S. Ohnuma, J. Magn. Magn. Mater. 156 (1996) 311.
[3] A.B. Pakhomov, X. Yan, B. Zhao, Appl. Phys. Lett 67 (1995) 3497.
[4] K. Yakushiji, S. Mitani, F. Ernult, K. Takanashi, H. Fujimori, Phys. Rep. 451 (2007) 1.
[5] M.A.S. Boff, S.R. Teixeira, J.E. Schmidt, A.B. Antunes, Appl. Phys. Lett. 85 (2004) 757.
[6] B.I. Shklovskii, B.Z. Spivak, Hopping Transport in Solids, in: M. Pollak, B. Shklovskii (Eds.) (Eds.), Modern Problems in Condensed Science, vol.28, Elsevier Science, Amsterdam, 1991 Chapter 9).
[7] M.A.S. Boff, J. Geshev, J.E. Schmidt, W.H. Flores, A.B. Antunes, M.A. Gusmão, S.R. Teixeira, J. Appl. Phys. 91 (2002) 9909.
[8] M.A.S. Boff, F. Casarin, L.G. Pereira, A.B. Antunes, Physica B 406 (2011) 1833.